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For the Contract N00014-85-K-0365

"Computational and Experimental Investigation  
of Elastic-Plastic Fracture under Dynamic Conditions"

Period Covered: April 16, 1985 to April 15, 1986

from

C. F. Shih  
Division of Engineering  
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## DIVISION OF ENGINEERING

Brown University  
Providence, RI 02912

July 18, 1986

To: Dr. Y. Rajapakse, Scientific Officer, ONR  
From: C. F. Shih  
Re: Final Report on ONR Contract No. N00014-85-K-0365

As a final report on this contract, I am submitting the attached list of reports and papers that have resulted from our research work under this contract. I have also enclosed one copy of each report and paper. Progress on the project has been summarized in the Annual Report submitted to the Mechanics Division of ONR, and the details of the work may be found in the enclosed reports and papers. I will cite several of the major accomplishments of the work below.

Our studies on dynamic fracture have led to the concept of a transition time [2,3]. The response of a ductile fracture specimen can be characterized by a short-time response dominated by discrete waves, an intermediate-time response dominated by the structural inertia and kinetic energy and a long-time response dominated by deformation energy (or stress work). The transition time,  $t_T$ , is defined as the time beyond which the total deformation energy exceeds the total kinetic energy of the specimen. Using dimensional and elementary model analyses, we have obtained a simple formula for the transition time. The formula has been verified by two-dimensional and three-dimensional full-field finite element analysis of a dynamically loaded three-point-bend ductile fracture specimen. While the transition time can serve to distinguish the short-time from the long-time response, it has an additional role in nonlinear fracture mechanics which is discussed in the next paragraph.

If the material is ductile and fracture initiation takes place after extensive yielding of the ligament, the J-integral may be adopted as the characterizing parameter for fracture toughness. However, during the early stages of a dynamic loading process when discrete waves form an important part of the total mechanical field, a significant time may be required for a J-controlled nonlinear crack tip field to become established. Furthermore J cannot be determined by any direct means from a remote load and deformation history until a sufficient time has elapsed and the crack tip field has stabilized. The transition time is an estimate of the elapsed time necessary to achieve these conditions. Consequently the three-point-bend specimen can be expected to provide interpretable fracture toughness data if fracture occurs beyond the transition time.

We have successfully carried out three-dimensional elastic-plastic analysis of a dynamically loaded three-point-bend ductile fracture specimen. The specimen is loaded to fracture initiation by a rapidly applied force on the mid-span of the beam.

It is assumed that the fracture initiates after substantial plastic deformation occurs in the uncracked ligament and the J-integral has been adopted as a pertinent parameter characterizing the intensity of crack tip field. Based on a fundamental crack tip integral [1], a domain integral form of J is derived for the three-dimensional crack front subject to transient loadings. The domain integral has been shown to provide accurate pointwise values of J from computed field quantities. We have shown that our formulation is ideally suited for three-dimensional analysis. The variation of J along the crack front and its dependence on loading rate and elapsed time are detailed in reference [3]. The analysis provides a basis for interpretation of the dynamic fracture experiments being carried out by Gudas and coworkers [4].

Chia-feng Shih  
C. F. Shih  
Professor of Engineering

xc: C. Cometta, Executive Officer, Division of Engineering



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List of Publications

ONR Contract No. N00014-85-K-0365

"Computational and Experimental Investigation  
of Elastic-Plastic Fracture under Dynamic Conditions"

- [1] T. Nakamura, C. F. Shih and L. B. Freund, "Computational methods based on an energy integral in dynamic fracture," International Journal of Fracture, Vol. 27, (1985), pp. 229-243.
- [2] T. Nakamura, C. F. Shih and L. B. Freund, "Analysis of a dynamically loaded three-point-bend ductile fracture specimen," Brown University Report ONR 0365/1, (1985), Engineering Fracture Mechanics, in print.
- [3] T. Nakamura, C. F. Shih and L. B. Freund, "Three-dimensional elastic-plastic analysis of a dynamically loaded three-point-bend fracture specimen," work in progress, to be presented at the 3rd International Symposium on Nonlinear Fracture Mechanics, October 1986.
- [4] E. M. Hackett, J. A. Joyce and C. F. Shih, "Measurement of Dynamic Fracture Toughness of Ductile Materials," work in progress, to be presented at the 3rd International Symposium on Nonlinear Fracture Mechanics, October 1986.

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ANALYSIS OF A DYNAMICALLY LOADED  
THREE-POINT-BEND DUCTILE  
FRACTURE SPECIMEN

by

T. Nakamura, C. F. Shih and L. B. Freund

Division of Engineering, Brown University  
Providence, RI 02912, U.S.A.

Office of Naval Research  
ONR0365/1  
December 1985

## Computational methods based on an energy integral in dynamic fracture

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(Received September 1, 1984)

### Abstract

Developments in the use of the crack tip energy flux integral in computational dynamic fracture mechanics over the past few years are reviewed. An expression for the crack tip energy flux in terms of near tip mechanical fields which is valid for general material response is derived. It is then demonstrated that certain useful energy integrals may be extracted from the general result by invoking the appropriate characterization of material response. Several alternative representations of energy flux in the form of integrals over some finite region around the crack tip are presented and compared with a view toward implementation in finite element simulation studies.

### 1. Introduction

The first crack tip contour integral expression for elastodynamic energy release rate was proposed by Atkinson and Eshelby [1], who argued that the form for dynamic growth should be the same as for quasi-static growth with the elastic energy density replaced by the total mechanical energy density, that is, the elastic energy plus the kinetic energy. The equivalent integral expression for dynamic energy release rate in terms of crack tip stress and deformation fields was subsequently derived directly from the field equations of elastodynamics by Kostrov and Nikitin [2] and by Freund [3]. They enforced an instantaneous energy rate balance for the time-dependent volume of material bounded by the outer boundary of the solid, the crack faces, and small loops surrounding each moving crack tip and translating with it. By application of Reynold's transport theorem [4] and the divergence theorem an expression for crack tip energy flux in the form of an integral of field quantities along the crack tip loop was obtained. A result which is applicable to a much broader range of material response and which contains the earlier elastodynamic result as a special case is derived here, with an observation made by Eshelby [5] on the form of the equations of motion as a point of departure. A similar result has also been obtained by Willis [6].

In the analysis of dynamic crack phenomena by means of computational methods, such as the finite element method, a fundamental difficulty is encountered in efforts to compute values of the crack tip energy flux versus time or amount of crack growth. The difficulty arises from the fact that, on the one hand, the crack tip energy flux is defined in terms of the values of field quantities for points arbitrarily close to the crack tip while, on the other hand, it is precisely for points near the crack tip for which the accurate calculation of field quantities is most difficult. In an effort to circumvent this difficulty, finite domain integrals have been introduced for the computation of dynamic energy release rate by Kishimoto, Aoki and Sakata [7,8], by Atluri [9], and by Nishioka and Atluri [10-12].